1. The WCSDEP convention

This document describes an appendix to FITS WCS Paper I being proposed by Doug Mink `<dmink@cfa.harvard.edu>` and Steve Allen `<sla@ucolick.org>`. This is Revision: 1.17 of Date: 2002/09/06 08:29:21 .

Paper I defines WCS keywords which describe the transformation from FITS pixels to world coordinates in a single pass. The appendix proposes another interpretation of the WCS keywords which permits a complete WCS to be constructed by concatenating two or more of the alternate axis descriptions.

1.1. Justifications for WCS concatenation

The proposed appendix and the changes to the main body of Paper I required to implement it are given in section 2 of this document. Section 1 of this document is preliminary text and is not part of the proposed appendix. It provides some justifications for permitting concatenations of WCS transformations.

1.1.1. Concatenation for Legacy Data Acquisition Systems

The single-pass WCS scheme is suitable for FITS files which are produced after processing. Some data acquisition systems, however, traditionally present a raw image to the observer without significant delay. (Indeed, under the operational constraints of some observatories this raw image is the only form which is ever archived.) It may be infeasible for such systems to insert a precise celestial WCS into the header. Nevertheless, it may be possible for the data acquisition system to insert an approximate WCS into the FITS header. Even an approximate WCS is extremely valuable both for archival purposes and for "quick-look" analysis of the data using a simple FITS image viewer.

In concept the transformation from pixels to world coordinates is usually composed of many steps. Here is an example of a typical transformation chain inherent to an optical system.

FITS pixels =A⇒ CCD amplifier pixels =C⇒ CCD pixels =F⇒ camera focal plane coordinates =B⇒ telescope boresight coordinates =Z⇒ apparent celestial coordinates =S⇒ catalog celestial coordinates

Transformation `A` is linear and depends on the on-CCD pixel binning, the number of prescan pixels saved, and whether the pixel ordering is flipped when writing the FITS array. These are often subject to change between one exposure and the next, so the data acquisition system must document this.

Transformation `C` is linear and depends on the design layout of the particular CCD. This transformation is suitable for storage in a configuration file.

Transformation `F` is usually linear and depends on the design of the particular instrument in the focal plane. This transformation is suitable for storage in a configuration file.

Transformation `B` depends on the entire optical system of the camera and telescope. Conceptually it is a zenithal angular coordinate system tied to the structure of the telescope. A precision description of it may require significant numbers of distortion parameters. This transformation (or the concatenation of `F` and `B`) is suitable for determination once at the time of instrument commissioning and subsequent storage in a configuration file.

Transformation `Z` depends on the Euler angles of the telescope pointing. These should be available from the telescope control system.

Transformation `S` depends on the atmospheric refraction and stellar aberration. For the purposes of an approximate WCS inserted into the FITS header in real time it might be ignored.

The multi-step transformation has the additional ability to communicate the individual uncertainties involved in each step of the chain using the CRDERia and CSYERia keywords. For the chain described here, steps `A` and `C` would have zero random and systematic error. Steps `Z` and `S` would typically have a smaller random and larger systematic error. This provides a syntax for telescope engineers to communicate their knowledge of the system characteristics.

In the ideal situation a data acquisition system would contain a processing pipeline which determined and inserted a precision WCS into each FITS header. In such cases it would usually be the case that the entire chain of transformation `FBZS` would be described as a single step, and the uncertainties would be quite small.

In the real world it may be that a data acquisition system cannot even perform the concatenation of the above transformations. It may, however, be possible for a system to copy boilerplate pieces of a multi-step transformation and simply insert the requisite parameters which it does know.

1.1.2. Concatenation for Multiple WCSs with Distortions

Paper II presents examples using several alternate versions of WCS to transform to different celestial coordinate systems. Paper III presents examples using several alternate versions of WCS to transform to different spectral coordinate systems. Optical imaging systems often have significant distortions which require corrections of the sort to be presented in paper IV. Typical optical distortion corrections are likely to require dozens, if not hundreds, of distortion parameters (DVi_ma).

Under the formalism of the main body of paper I the only way to describe multiple WCSs with high-precision is to replicate the distortion parameters in each alternate WCS. This potentially leads to a large expansion of the FITS header with redundant data.

The concatenation of WCS versions permits the keywords for complex distortion to be included in only one WCS. This WCS may be reused for several different celestial and/or spectral coordinate systems.

1.2. Summary and remarks

As an appendix this is not part of the WCS standard. This appendix exists in solely in order to reserve the `WCSDEP`a keywords and suggest a usage for them. Other than that it does not modify any of the main WCS standard.

This appendix should have no effect on the adoption of the main standard.

The syntax and semantics of WCS concatenation introduced by this appendix were initially implemented in the WCSTools package by Doug Mink of Harvard/CfA. They have been operational since the 2.9.0 release of WCSTools in 2001 February. (The WCSTools package admits a slightly broader interpretation where the value of `WCSDEP`a may be a character string which matches the value of some other `WCSNAME`a keyword.)

The inputs to downstream WCSs in a concatenation chain are not pixels per se as described by the main standard. However, the main standard admits inputs which are fields from columns of FITS tables. Nothing in the main standard can require that the table entries actually be derived from pixel-oriented sources.

Some of the example WCS transformations given in the justifying preamble convert from one spherical coordinate system to another spherical coordinate system by doing nothing more than rotating via Euler angles. This sort of transformation already exists in the main standard as the CAR projection described by Calabretta in paper II. In such cases the `CRPIX`j values of the WCS seem likely to be zero.

It remains to be decided whether it is necessary to indicate in the text that the default value of `WCSDEP`a is a zero-length (i.e., NULL) string as defined in NOST 100-2.0 section 5.2.1. Note that this differs from the defaults for `CTYPE`ia and `CUNIT`ia which are blank strings.

2. Additional text for the main body of Paper I

In order for the Appendix to work there must be a small amount of additional text in the main body of FITS WCS Paper I. The purpose of that text is to reserve the `WCSDEP`a keywords and indicate how they affect the interpretation of the WCS with version a.

This text follows the lead set in numerous paragraphs of section 8.3 of NOST 100-1.2, which itself was derived from the original binary tables paper.

2.1. Additional text for section 2.5

The set of keywords named `WCSDEP`a is reserved to indicate that the interpretation of WCS keywords is not defined by the main body of this paper. The index character a is permitted to have the values blank and `A` through `Z` specifying the coordinate version. The existence of a `WCSDEP`a card with a non-NULL value means that a FITS interpreter should not attempt to use WCS version a in the standard manner. The value field of the `WCSDEP`a keywords shall contain a character string describing how to interpret WCS version a. A suggested convention for interpretation of the WCS is described in Appendix A.

2.2. Additional record for Table 1

Keyword Description	Concatenation required
Primary Array	`WCSDEP`a
BINTABLE vector	
primary	`WCDP`n
alternate	`WCDP`na
Pixel List	
primary	–
alternate	–

(Note that the WCSDEP convention cannot be used with pixel lists because the grouping and ordering of such axes is not defined.)

2.3. Additional record for Table 7 of Paper I

Keyword	`WCSDEP`a
Type	character
Sect.	2.5, App. A
Use	indicates WCS concatenation
Status	new
Comments	see Appendix A.

Appendix A: Concatenation of FITS World Coordinate Systems

In the main body of this paper the inputs for the WCS transformations are either FITS pixel array coordinates or table column entries. The principal WCS and all the alternate versions transform directly from the input coordinates to the output in a single pass. However there are some conditions under which it may be infeasible for a FITS file writer to construct a single-pass WCS. This appendix describes an alternate convention for the interpretation of the WCS keywords which permits a WCS to be constructed via concatenation of two or more versions of WCS specified in the FITS header.

A.1. Concatenation Keyword and its Interpretation

The presence of the FITS keyword `WCSDEP`a with a non-NULL value indicates that the WCS with version a depends on the results of another WCS transformation. The value of `WCSDEP`a should be a character string indicating the version of another WCS which must be performed prior to the application of the WCS with version a. The keyword `'WCSDEP '` (indicating the default WCS where a is an ASCII blank) is permitted to support interchangeability of WCS versions, but it should be used with caution. The WCS version specified by the value of a `WCSDEP`a

card is hereafter called the antecedent WCS. Multiple concatenations are permitted so long as there is no circular dependency in the sequence. If any antecedent WCS in the sequence does not exist, then the resulting WCS is not defined.

The character string value of WCSDEPa is permitted to indicate the antecedent WCS by matching either the WCS version index character a of another WCS or the value of the WCSNAMEa keyword for another WCS. In order to avoid the obvious self-dependency, the value of WCSDEPa may not match the value of the WCSNAMEa keyword for its own version, nor may it match the single character of its own version unless that character is the value of WCSNAMEa for some other version of WCS.

If the value of WCSDEPa matches the value of exactly one other WCSNAMEa keyword, then the WCS version of that other WCSNAMEa keyword is the antecedent. Otherwise, if the value of WCSDEPa is a single uppercase character, then that character specifies the WCS version of the antecedent. If the value of WCSDEPa matches neither of these criteria, then its antecedent WCS is undefined and the WCS with version a is also undefined.

Note that this permits WCS concatenation to add additional apparent confusion to the situation where `WCSNAMEA = 'B'`. However, single character values of WCSNAMEa are not precluded by the main body of this paper, and despite appearances their meaning in the presence of concatenation is well defined.

Note also that this permits the antecedent WCS to be specified by a single character even if there are no WCS cards for the antecedent version. In such a case the antecedent WCS is taken to be the identity transformation.

A.2. Computation of WCS Concatenation

In the absence of WCSDEPa the coordinate transformation with version a does not depend on any other WCS, and the computation of its values proceeds as defined in the main body of this paper. In the presence of WCSDEPa the output coordinates from the antecedent WCS are used as inputs for the WCS with version a. Other than this difference of input, the calculation for each component WCS is performed as defined in the main body of this paper. The order in which the antecedent output coordinates are mapped to the inputs is specified by the CTYPEia cards of the antecedent.

For example, `WCSDEPB = 'A'` indicates that the WCS with version B depends on the antecedent WCS with version A. The world coordinate tranformation for WCS version A must be applied first, and its coordinate outputs are used as inputs to the WCS with version B. If the CTYPEiA cards of the antecedent WCS specify a linear projection then the order of the input coordinates (corresponding to CRPIXjB) simply matches the matrix ordering of the antecedent output coordinates (corresponding to CTYPEiA and CRVALiA). If the CTYPEiA cards of the antecedent WCS specify a non-linear transformation then the order of the inputs (corresponding to CRPIXjB) matches the ordering of the output CTYPEiA cards after applying the non-linear transformation. In other words, if the antecedent WCS has

CTYPE1A = 'RA---alg'
CTYPE2A = 'DEC--alg'

then the first input to WCS B is the output RA coordinate and the second input is the output Dec coordinate. Similarly, if the antecedent WCS has

CTYPE1A = 'xLAT-alg'
CTYPE2A = 'xLON-alg'

then the first input to WCS B is the output latitude coordinate and the second input is the output longitude coordinate.

A.3. Usage of WCS Concatenation

The intended meaning of a WCS version that employs a WCSDEPa card may not be recognized by existing software systems which have implemented draft versions of the WCS papers. This is especially true for a `'WCSDEP '` card which asserts that the default WCS depends on another. Users of this convention should remain aware of the possibility of misinterpretation. WCS concatenation should be employed with caution.

However, construction of a single-pass WCS often requires a considerable amount of computation. The FITS file writer may have to combine many steps, some possibly non-linear, to produce each single-pass WCS that is desired in the FITS header. Such computations may be beyond the ability of the FITS file writers in some existing real-time data acquisition systems.

WCS concatenation shifts the burden from the FITS file writer to the file reader. Concatenation permits a FITS file writer to re-use complex (and possibly precomputed) components in several different WCS versions with no extra effort. Concatenation can increase the amount of useful WCS information that can be communicated in a FITS header. In some cases it may make WCS information available from a system which would otherwise be incapable of providing any WCS information.

Note that WCS B may assert that it depends on antecedent WCS A merely by having the FITS card `WCSDEPB = 'A'` with no other WCS keywords for version B being specified. This means that WCS B is simply an unmodified duplicate of WCS A being invoked by reference.

This convention is optional and will not preclude other conventions. This convention is not part of the World Coordinate System definition.